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Influence of high-frequency audibility on the perceived distance of sounds

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Summary
When listening in natural environments, normal-hearing (NH) listeners usually perceive sounds outside their head, i.e., externalized. Sounds perceived inside the head are called internalized. Hearing-impaired (HI) listeners have been reported to externalize sounds less accurately than NH listeners. In a study by Boyd et al. (2012), the average externalization ratings of NH listeners dropped and matched those of HI listeners when the signals were lowpass-filtered at 6.5 kHz. This suggested that reduced high-frequency audibility might cause a reduced externalization in HI listeners. The present study aimed at clarifying whether the perceived *distance* of sounds in HI listeners differs from NH data as well and, if so, whether distance-rating performance improves when reduced audibility is compensated for by amplification. Individual binaural room impulse responses (BRIRs) were measured for nine different loudspeaker distances. NH and HI listeners were asked to rate the perceived distance of processed speech samples in a MUSHRA-like test paradigm according to optical markers placed in the same workshop room where the BRIR measurements were performed. NH listeners rated the distance of unfiltered and lowpass-filtered speech, and HI listeners that of unfiltered speech and of speech amplified to compensate for their audibility loss. The results for NH listeners showed no systematic effect of lowpass-filtering the stimuli at 2 kHz or 6 kHz on distance ratings and the measured distance curves were much steeper than those found in the literature. Preliminary results for three HI listeners showed large inter-subject variability, but as a tendency, the distance rating seemed to vary with the energy content of the signal rather than the bandwidth, indicating that loudness might be a strong contributor to distance perception in HI listeners.

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1. Introduction

Localization of sound sources in natural listening environments not only involves the determination of the angle of incidence of the sound, but also the distance to the sound source. While there is a large body of literature available on the directional aspect of sound source localization, the determination of distance has received much less attention. Probably the most comprehensive review of this topic including a thorough investigation of the cues underlying distance perception can be found in [1]. A list comparing some of the key conditions and findings from several studies on distance perception is provided in [2]. One of the major findings in distance perception studies was that the dependence of the perceived distance on the actual (or simulated) sound source distance can be described by a power function with an exponent below one. The sound source distance is generally overestimated at close distances and progressively underestimated at far distances. The three primary physical cues for distance perception described in [1] are the intensity of the sound, the direct-to-reverberant sound ratio and spectral content. According to these cues, sounds are perceived farther away when they are lower in intensity, have a small direct-to-reverberant ratio and when the high-frequency content is low.

Two recent studies investigated the influence of the frequency content on the *externalization* of sounds. Even though the sensation of externalization may be assumed to be strongly related to distance perception, the dependence of externalization on the frequency content of the stimulus seems to differ from that observed in the case of distance perception. In [3], hearing-impaired (HI) listeners were reported to provide lower average externalization scores than NH listeners in an experiment where a virtual auditory space technique with individual binaural room impulse responses (BRIRs) was used. Furthermore, it was found that the average externalization rating of NH listeners dropped to the level of HI listeners when the stimuli were lowpass-filtered at 6.5 kHz to simulate a typical hearing aid bandwidth. A slight reduction of the externalization rating compared to the broadband speech baseline condition was also found in [4] for NH listeners in a similar experiment for stimuli lowpass-filtered at 4 kHz. These findings suggested that HI listeners perceive sounds less externalized than NH listeners and that reduced audibility at high frequencies might be the main reason for this degradation.

These two externalization studies inspired the current investigation that used a virtual auditory space technique similar to that in [2] to investigate whether the perceived *distance* of sounds in HI listeners also differs from that in NH listeners and, if so, whether this difference can be accounted for by reduced audibility at high frequencies in the HI listeners. All experiments were approved by the Science-Ethics Committee for the Capital Region of Denmark (reference H-3-2013-004).

2. Methods

2.1. Listeners

Ten NH listeners (one female, average age 29), and (so far) three HI listeners (one female, average age 62) participated in the experiment. The three HI listeners had normal thresholds or only a mild hearing loss at the low frequencies and a sloping hearing loss towards high frequencies with maximum thresholds of 50, 65, and 80 dB HL, respectively, at 8 kHz. Two of the listeners had symmetric hearing losses with maximum differences of 10 dB between the ears, whereas the third one showed a more asymmetric hearing loss with differences up to 30 dB at single frequencies. Only one of the listeners (the one with the most severe hearing loss) was a hearing aid user.

2.2. BRIR measurements

Individual BRIRs were measured for each listener with a Dynaudio BM6P loudspeaker at nine log-spaced egocentric distances (0.43, 0.61, 0.86, 1.22, 1.72, 2.44, 3.45, 4.88, and 6.9 m, as in [2]) at an azimuth angle of 25° relative to the listener. The listeners were blindfolded before being guided into the experiment room, a workshop of about 12.65 x 6.75 x 3.10 m with an acoustic ceiling and an average reverberation time T_{30} of about 0.6 s. During the measurement, the listeners were seated in a listening chair and provided a small headrest to help keeping the position of the head fixed. The BRIRs were measured at the entrance of the open ear canal with omnidirectional DPA 4060 lapel microphones attached to the pinna with a wire hook, using six repetitions of a 5 s logarithmic sine sweep and a deconvolution method according to [5]. The recordings were made through an RME Babyface audio interface that was also used for audio playback during the experiment. For increased headroom for the headphone playback, a Behringer Powerplay Pro-8 headphone amplifier was inserted between the audio interface and the headphones. Even though measurements with an open ear canal have been shown to result in higher variability of the measured response as compared to measurements with an occluded ear canal [6], this method was chosen here for practical reasons, because occlusion of the ear canals and the resulting sound attenuation would have further complicated the communication with the HI listeners during the measurement. After the BRIR measurements, the listeners put on a pair of Sennheiser HD 800 headphones and the headphone impulse response (HPIR) was measured with 10 repetitions of a 2 s sine sweep. After the measurement, the blindfold and the microphones were removed.

2.3. Stimuli

For each experimental run, a random sentence from the Danish HINT speech test corpus [7] was convolved with the measured BRIRs and the inverse of the HPIRs. The resulting auralized signals were band-limited between 50 and 15000 Hz with 6th order Butterworth filters (Broadband condition). Besides the broadband condition, the NH listeners were tested with lowpass-filtered stimuli, either with a cutoff-frequency of 6 kHz to simulate the limited bandwidth of a hearing aid or with a cutoff-frequency of 2 kHz to simulate a hearing loss. Both lowpass-filters were realized as 32 tap Hamming-window based FIR filters. Apart from the band-limitation, all of the acoustic distance cues available in the room remained untouched.

For the HI listeners, five conditions were tested in the experiment. The overall rationale for the test conditions was to compensate for the individual hearing loss by providing gain up to the cutoff-frequency in each run with the intention to make the signals as equally audible to the HI listeners as possible. Using this method, two different degrees of hearing loss were simulated by applying lowpass-filtering to the signals at 1 kHz and 3 kHz, respectively. The third condition again simulated the limited bandwidth of a hearing aid with the same cutoff-frequency of 6 kHz as for the NH. The fourth condition provided gain up to 10 kHz, which was chosen as the maximum frequency for which a hearing loss compensation seemed feasible. Finally, the listeners were also tested "unaided", i.e. presented with the full broadband signal without

Table I. Listening test conditions for NH and HI listeners.

Normal–hearing	Hearing–impaired
Lowpass 2 kHz	Lowpass 1 kHz
Lowpass 6 kHz	Lowpass 3 kHz
Broadband (50 Hz–15 kHz)	Lowpass 6 kHz
	Lowpass 10 kHz
	Broadband

any hearing loss compensation. An overview over the listening test conditions can be found in Table I.

To compensate for the loss of audibility of the HI listeners, an individual compensation filter was designed for each ear based on the CAMEQ prescription for linear hearing aids [8]. The underlying goal of this fitting rationale is to yield equal loudness within the frequency range of speech input signals with an input level of 65 dB SPL as evaluated by the loudness model presented in [9]. The result is essentially a half-gain rule fitting rationale [10] with correction terms for individual frequency bands. CAMEQ provides gain prescriptions only for frequencies up to 5 kHz and recommends to limit the gain at higher frequencies to the value at 5 kHz. In this study, the correction terms for frequencies above 5 kHz were set to zero, but the gain was still provided to increase high-frequency audibility. For the band-limited test conditions, the gains above the cutoff-frequency were set to zero and the prescribed gains were interpolated to generate the desired filter magnitude response. Above the cutoff frequency, the magnitude response was designed to decay to 0 dB linearly (on a dB scale) within 1/3 octave. The impulse response of the linear phase compensation filter was then generated with the frequency domain sampling method as implemented in the `fir2` Matlab function.

2.4. Experimental procedure

The listeners were instructed to judge the distance of the auditory event on an absolute scale in m provided by visual markers at distances of 2, 4, 6, and 8 m in the workshop room (see Figure 1 for a photograph of the experimental setup). The distance was rated via a modified MUSHRA (ITU-R BS.1534-1) Matlab user interface with a playback button for each stimulus (labelled "A" to "I") and a slider with the same scale as provided in the room to rate the perceived distance. The listeners were instructed to rate the distance as zero if the sound was perceived inside the head. In each run, stimuli with the same bandwidth for all nine measured distances were randomly assigned to the sliders. The listeners could listen to the stimuli as often as they needed to find their distance rating. All bandwidth conditions were tested once to train the listeners and repeated four times in the actual experiment for the NH listeners and six times for the HI.

Figure 1. Photograph of the listening test setup in the workshop room with visual markers at 2, 4, 6, and 8 m.

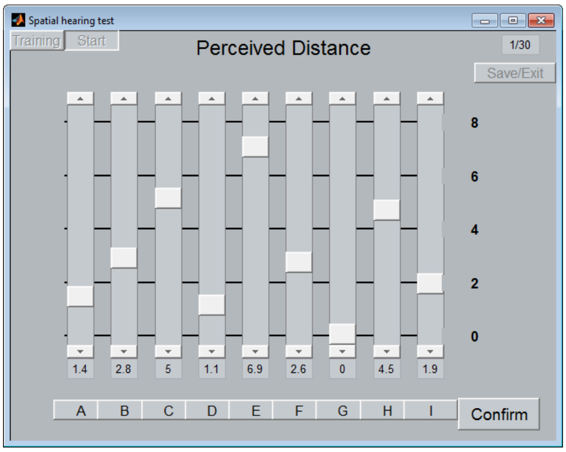

Figure 2. Screenshot of the GUI used in the listening experiment. The buttons (A-I) start the playback of a sound sample and the sliders are used to give a distance rating for the corresponding sample according to the scale in the room

3. Results and discussion

Figure 3 shows the average value and standard deviation of the perceived distance for all NH listeners in the broadband condition (squares) and for the stimuli lowpass-filtered at 6 kHz (triangles) and 2 kHz (circles). For the two shortest distances, the auditory image was, on average, perceived closer to the listener than the auralized distance. For medium distances between about one and five metres, the average distance estimates were fairly close to the veridical values (light grey, dash-dotted line in Figure 3) whereas the sounds were perceived slightly closer than the actual loudspeaker position in the BRIR measurement for the farthest distance.

These findings are clearly in contrast to the average data presented in [2], which are indicated by the grey dashed line in Figure 3, where the listeners typically overestimated the distances at short source distances and underestimated the farther distances, a behaviour that has also been found in most other studies on auditory distance perception (see summary table in [2]). One reason for this discrepancy might be that the measurements in [2] were conducted in an auditorium, whereas the experiment was performed with virtual sounds presented over headphones in a listening booth without visual cues. In contrast, the listeners in the present study performed the task in the *same* room where the BRIRs had been measured and where visual distance cues were provided. The experimental conditions in the present study were thus much closer to those of a recent study investigating the influence of visual anchors on auditory distance perception [11]. Comparing our results to the ones from [11], the data are consistent with the case where visual markers were present. This suggests that auditory distance perception is strongly influenced by, and much more precise in the presence of, visual cues.

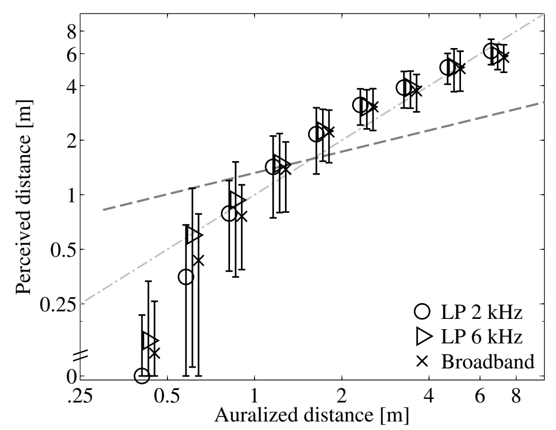

Figure 3. Perceived auditory distance over auralized sound source distance. The grey, dashed line represents the average distance rating found in [2], the light-grey, dash-dotted line indicates the veridical values.

Comparing the distance ratings for the different bandwidth conditions, no clear influence of the lowpass-filtering could be found in the NH data. This suggests that distance perception is rather robust with respect to the high frequency content, unlike externalization where [3] and [4] found that even moderate lowpass-filtering caused a significant reduction of the percept.

The data for the three HI listeners are shown in Figure 4. Here, the results are presented for each listener individually, because the data show a large spread across listeners compared to the NH data. The data for listener 1 (top panel in Figure 4) are similar to the NH data from Figure 3. Also this listener generally underestimated the source distance at close range and showed close to perfect performance at medium distances. At close distances some differences occurred between the conditions. As a tendency, the narrowband conditions seemed to be perceived at greater distance. This is consistent with the cues for auditory distance perception reported in [1]. With increasing bandwidth, the overall intensity of the signal increases, and the sound signal should be perceived as being closer. The results for listener 2 (middle panel in Figure 4) showed a wide spread in the data, but again, the conditions with narrow bandwidth tended to be perceived farther away than the ones with wider bandwidth. This also includes the 'unaided' condition. Due to the hearing loss, the effective bandwidth of the signal in this condition was between the 3 kHz and the 6 kHz condition. The listener reported to consistently hear the speech samples as coming from behind. These front-back confusions are not uncommon in a virtual auditory environment and has often been reported in other studies (see e.g. [12] for an investigation). Here, the effect might have been emphasized by the fact that the listener had an asymmetric hearing loss and was therefore provided with asymmetric gains for the left and right ears. This changed the interaural level differences that are normally encountered by the listener. The front-back confusion might explain the larger spread in the data compared to the other two HI listeners.

Listener 3 seemed to have used the strategy to rate the signal that sounded the farthest towards the end of the scale (8 m). The closest signal was rated towards the minimum distance (0 m) and the rest of the signals was ordered in between with a roughly constant spacing. This might explain the very consistent ratings across all tested conditions seen in the bottom panel of Figure 4. Such a strategy would also explain the shape of the curve, which would occur when the log-spaced auralized distances are rated on an equidistant scale. If a similar strategy was employed by more test subjects, this also suggests that the observed shape of the distance curves might not only be due to the influence of the visual system (cf. [11]), but at least in part also an artefact of the response method.

The CAMEQ prescription method only recommends gains up to 5 kHz. Above that frequency, the gain is limited to the value at that frequency. Even though higher gains were provided at high frequencies in this study, it still needs to be investigated, whether the gain is actually high enough to ensure audibility of at least parts of the high-frequency content of speech.

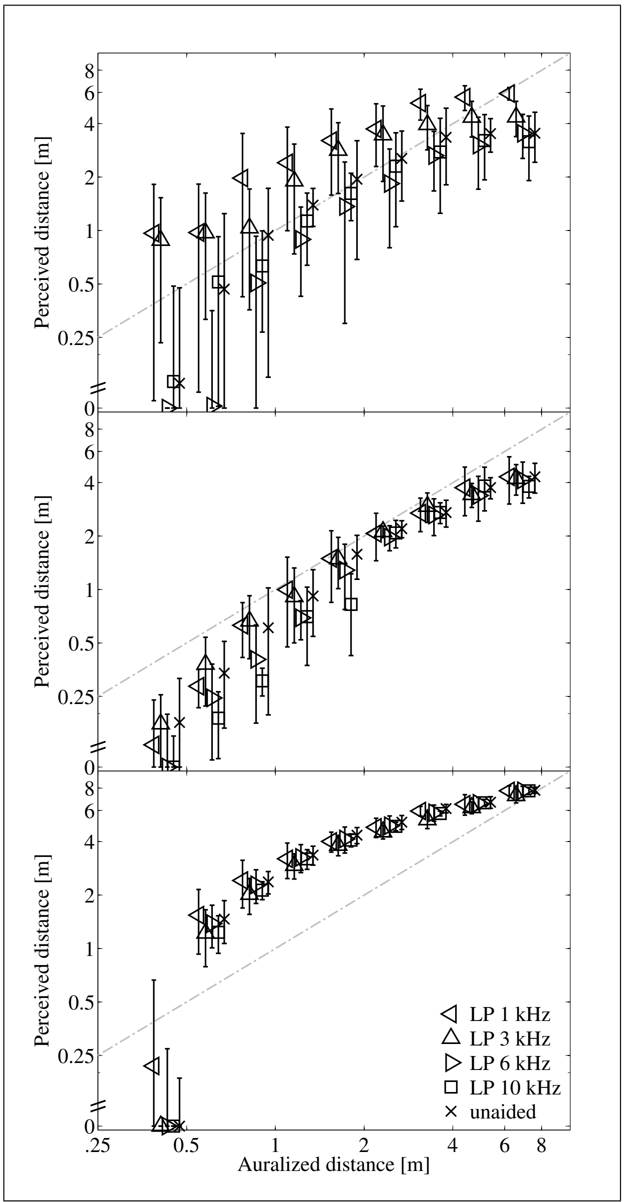

Figure 4. Distance rating results for the HI listeners. Because of the large inter-subject variability, mean values and standard deviations are shown for the individual data.

The results indicate that the cues for auditory distance perception may differ from those crucial for externalization. While reduced bandwidth was reported to decrease the percept of externalization [3, 4], the bandwidth reduction also reduced the overall intensity of the stimulus, and thus the perceived loudness. Loudness is one of the main cues for distance perception [1], and it was found that especially HI listeners seem to heavily rely on it and have difficulties to decide which sound source is farther away, if loudness differences are compensated for [13].

4. Conclusion

The listeners in this study were able to rate the perceived distance of the presented stimuli consistently. The distance functions were found to be quite different from the ones usually reported in the literature. Here, the auralized source distance at close distances was generally underestimated rather than overestimated, and the functions did not show the typical highly compressive behaviour. It still needs to be investigated, how much of this difference is due to the availability of visual cues during the experiment and how the experimental procedure with the MUSHRA-like GUI influences the results. Also the influence of running the experiments in the same room where the BRIRs were measured, as opposed to measuring in a listening booth, needs further investigation.

NH listeners did not show a clear dependence of the perceived distance on the bandwidth of the stimuli. For two of the three HI listeners, there seemed to be a tendency that providing larger bandwidth decreased the perceived distance of the auditory event. It seems that, even though related, the percepts of distance and externalization are clearly different and rely on different cues.

Acknowledgement

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